EO-ALERT: Machine Learning-Based On-Board Satellite Processing for Very-Low Latency Convective Storm Nowcasting

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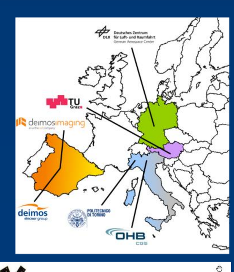
Introduction

Recent years have seen a sharp growth in Satellite Earth Observation (EO) product applications, such as environment and resource monitoring, emergency management and civilian security, leading to an increase in demands on amount, type and quality of remote-sensing satellite data and efficient methods for data analysis. While modern Machine Learning (ML) and Artificial Intelligence (AI) algorithms are revolutionizing automatization, speed and quality of data analysis, the use of satellite EO-based image products for rapid meteorological and civil security applications is still limited by the bottleneck created by the classical EO data chain, which involves the acquisition, compression, and storage of sensor data on-board the satellite, and its transfer to ground for further processing. This introduces long latencies until product delivery to the end user.

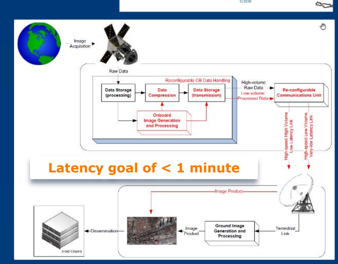
The H2020 EU project EO-ALERT (http://eo-alert-h2020.eu) led by DEIMOS, addresses this problem through the development of a next-generation EO data processing chain that moves optimised key elements from the ground segment to on-board the satellite. Applying optimized ML methods, EO products are generated directly on-board the spacecraft.

The capabilities of the EO-ALERT product and its remote sensing data processing chain are demonstrated in an application scenario for meteorological nowcasting and very short-range forecasting for early warnings of convective storms. Its 3-step-approach consists of: Candidate convective cell extraction from satellite imagery, tracking of cell positions and features extracted from infrared channels over time, and the discrimination of convective cells in their different stages of evolution using machine learning classifiers (Gradient Boosting). Training and validation are performed using a specifically created dataset of MSG-SEVIRI images and OPERA weather-radar network composites corresponding to 205 days between 2016 and 2018 exhibiting extreme convective weather events. The performance is further compared against NWCSAF's Rapid Developing Thunderstorms (RDT-CW) product. Through on-board implementation, the system is able to detect convective storm cells and predict their future trajectories, and to send the processed information to ground, within 5 minutes of the observation.

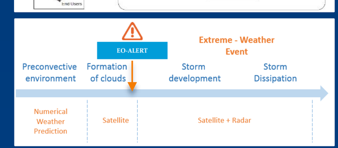
Project Overview



EO-ALERT is a European Union's Horizon 2020 project led by DEIMOS which started in 2018 and will conclude in 2021, with the involmenet of 6 European partners and the Agencia Estatal de Meteorología (Spain) as consultant.



Goal: Development of a new approach for the provision of very low latency EO data products, driven by operationally relevant application scenarios. The Extreme Weather Scenario will provide a very low latency product for convective storm nowcasting to complement existing solutions like NWCSAF's Rapidly Developing Thunderstorm (RDT)[2] product.

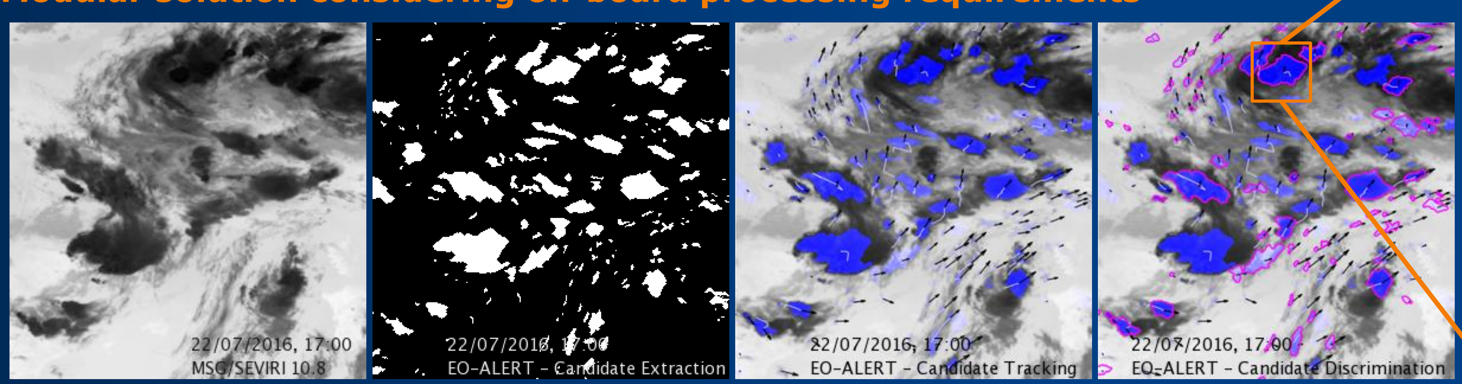


Idea: Move key EO data processing elements from the ground segment to the satellite and execute image processing and machine learning algorithms on-board to predict the probability for convective storms in pre-, mature and decaying stage.

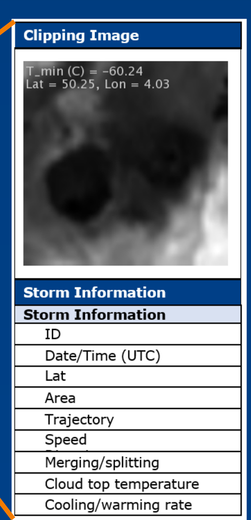
Extreme Weather Scenario

Algorithmic Approach for On-Board Processing

Modular solution considering on-board processing requirements

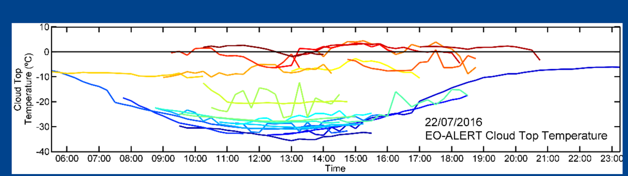


Input image SEVIRI IR10.8 | Identification of candidate convective cells (Computer Vision) | Tracking and feature extraction (Computer Vision) | Discrimination of convective/non-convective cells (Machine Learning)



Alert creation

Candidate Cell Extraction: Radiances from SEVIRI IR10.8µm images are converted to brightness temperature images. Temperature minima with a temperature difference between cell top and cell base greater than 6° are detected, the cell boundaries corresponding to each minimum are found, and a candidate mask is created.



Candidate Cell Tracking: In order to gather information on the evolution and movement of cells, their trajectory is followed over subsequent acquisition times. Cells are matched to those found in the previous image based on spatial overlap in subsequent candidate maps. Ambiguities (splitting, merging of cells) as well as the disappearance and formation of cells are handled.

Candidate Cell Discrimination is performed by means of machine learning classifiers. Each cell is characterized by its corresponding radiances in 5 infrared channels in Meteosat-SEVIRI imagery and their respective evolution over time, and features for the classification are derived taking

- Historical data from up to 4 previous + present acquisition times: T_H=-60, -45, -30, -15, 0 min
- Area (in IR10.8µm channel), Statistics on Brightness Temperatures (5 Channels; Minimum, Maximum, Mean, 1st and 99th percentile), respective intra-channel differences between acquisition times (e.g., $\min(T_{0min}^{IR10.8}) - \min(T_{-15min}^{IR10.8})$) and inter-channel differences for same acquisition times (e.g., $\max(T_{0min}^{WV7.3}) - \max(T_{0min}^{WV6.2})$). This results in a maximum total number of 311 features per cell.

A Gradient Boosted Decision Trees (GBDT) ensemble technique is used for classification of convective/non-convective cells.

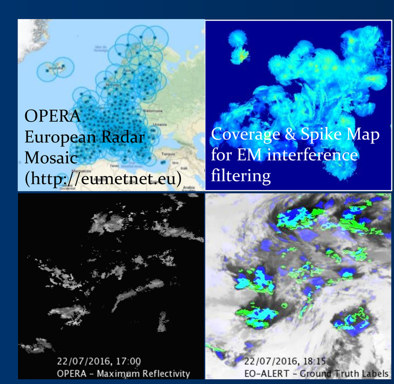
Alert Generation: Finally, alerts are created for cells which have been classified as convective. These alert messages, which contain the comprehensive characterisation details of the detected storms, are transferred to ground where they can then be evaluated. In contrast with the classical EO data processing chain this approach does not rely on the transfer of raw data to ground and thus greatly reduces the amount of data transmitted. Together with the EO-ALERT on-board data compression and high data rate communication links, this allows for very low latency product delivery.

A prototype of the image processing pipeline has been implemented and tested in MATLAB®, and an OpenCV/C++ implementation is being implemented for the final HW testing.

Extreme Weather Dataset

Input data for training and testing:

- Infrared data from GEO satellite: MSG-3/4 (SEVIRI instrument), 5 Channels: Water vapour - Ch05 (6.2 µm), Ch06 (7.3 µm); IR Window channels - Ch07 (8.7 µm), Ch09 (10.8 µm), Ch10 (12.0 µm).
- Data collected from 65 periods composed of a total of 205 days with storms (2016-2018), equalling 12000 images.
- Geographical Region of Interest: Europe (area covered by OPERA radar network)



Ground truth generation:

- Composites of SEVIRI images and OPERA weather radar network maximum reflectivity data
- Creation of a clutter map for removal of spurious echoes from EM interferences.
- Algorithm for convection detection in the radar composites based on Steiner et al.[3]
- Parallax correction of MSG-SEVIRI, re-projection of OPERA images to MSG grid.
- Convective labels assigned in composites based on spatial overlap between EO-ALERT candidate convective cells and OPERA convective cells.
- Unbalanced data: Ratio convective/non-convective cells ~12%

Preliminary Nowcasting Results

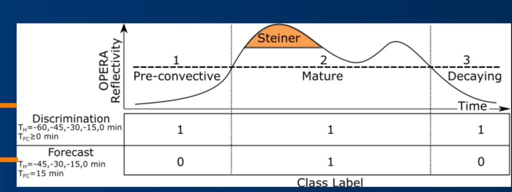
The **Definition of stages of cell evolution** is based on the temporal evolution of radar reflectivity in OPERA data:

Mature state: Cell-Ground Truth is convective[1], or OPERA reflectivity is above a threshold before/after it has been labelled convective.

Pre-convective, decaying: Cell-Ground Truth is convective[1] for a section of its trajectory, but OPERA reflectivity is below a threshold before (pre-convective) or after (decaying state).

Training of separate classifiers is done for varying availability of historical data (-60, -45, -30, -15 and 0 min), and for the following classification schemes, which differ in the way the different stages of cell evolution are treated:

1. Discrimination: The classifier is trained to discriminate a cell as convective if it is/will be convective at any moment of its lifetime. No distinction is made between the stages of cell evolution (Binary classification, positive labels for pre-conv., mature and decaying stage).
2. Forecast: The classifier is trained to discriminate a cell as convective only in the mature section of its trajectory. Historical data from timesteps T_H=-45, -30, -15 and 0 min is used to predict mature convective cells with a forecast lead time of T_{FC} = 15 min (Binary classification, positive labels for mature stage).
3. Convective Stage: Multiclass classification for the distinction of Pre-convective, Mature and Decaying cells will be integrated in the future.



Forecast

History (min)	POD	FAR	F1
0, -15, -30, -45	0.8	0.36	0.71
0, -15, -30	0.8	0.38	0.7
0, -15	0.8	0.4	0.71
0	0.78	0.45	0.65

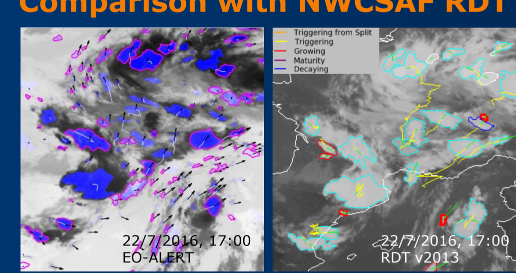
Discrimination

History (min)	POD	FAR	F1
0, -15, -30, -45, -60	0.8	0.35	0.72
0, -15, -30, -45	0.77	0.36	0.7
0, -15, -30	0.8	0.4	0.67
0, -15	0.78	0.42	0.67
0	0.8	0.51	0.61
RDT v2011[2*]	0.74	0.34	-

*) Results shown here are for the RDT verification setting "Moderate Lightning Hypothesis, Statistical element trajectory" which is similar but not identical to the EO-ALERT "Discrimination" scheme, and are reported for purpose of qualitative comparison.

The qualitative comparison with the operational NWCSAF RDT-CW (Rapidly Developing Thunderstorm - Convection Warning) product[4,5] shows compatible results for the candidate convective cell extraction and convective discrimination. Quantitative measures like the False Alarm Ratio (FAR) and Probability of Detection (POD) reach levels comparable to those of the RDT product when the full historical data is available, despite the fact that in contrast to the RDT no additional inputs from numerical weather model have been used. A full quantitative comparison will follow.

Comparison with NWCSAF RDT



Summary and Outlook

The EO-ALERT Extreme Weather Scenario aims at providing low-latency nowcasting of convective storms by performing machine learning-based EO satellite image analysis directly on-board the satellite. The results shown here illustrate the feasibility and applicability of the approach for convective storm nowcasting. The modular system consisting of candidate convective cell extraction, tracking & feature extraction and machine learning-based discrimination of convective storm obtains promising qualitative (comparison with the RDT-CW product) and quantitative (verification scores) results.

The suitability of the EO-ALERT on-board data processing and communication pipeline has already been demonstrated in analogue tests for a second application scenario (ship detection)[1,2]. An improvement of discrimination performance is expected to be achieved through model tuning. Considering the increasing availability of suitable on-board processing hardware, the application of Deep Learning-based algorithms is being investigated and promises a further improvement of performance. A further on-going activity focuses on the inclusion of Overshooting Top detection from SEVIRI's High Resolution Visible (HRV) channel.

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